REDUCTION OF CRASH SEVERITY THROUGH IN-VEHICLE SYSTEMS (IVS) SPEED CONTROL

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ABSTRACT

"The evidence of the effects of speed on accident severity is conclusive". (Kallberg/Luoma – Road Safety in Europe 1996).

It can be argued that road safety faces a severe problem: as the rate of road crashes per traveled kilometer decreases, the quantity of traveled kilometers increases and, therefore, the total quantity of road crashes tends to rise or, in the better of cases, to remain constant. In this context, if the decrease of the total quantity of victims of the automobile is desired, a serious effort to reduce the severity of road impacts should be made (without abandoning the intensification of road crash–prevention campaigns).

And since impact speed is a factor that has one of the greatest influence in the consequences of traffic crashes, the following should be highlighted:

– vehicles allow drivers to travel at very high speeds and many of them prefer to do so, exceeding by far the legal limits.
– some people even argue that it is safer to circulate at high speeds because some advantages are enjoyed (e.g.: it takes less time to arrive to destination, so drivers are less exposed to traffic dangers).
– human beings have a serious fascination for speed. In Aldous Huxley's words, speed seems to provide "the one genuinely modern pleasure".

To conclude, it does not seem to be possible for the circulation speeds to be reduced –on the contrary, they will probably be increased in most countries–; therefore, it is highly useful to limit the circulation speeds to those allowed by law in each type of road. A general approach to both the aspects of severity decrease through speed circulation reduction, and to the ways of doing this by GPS technology is proposed.

INTRODUCTION

"The vulnerability of the human body should be a limiting design parameter for the traffic system and speed management is central". (World Health Organization – World report on road traffic injury prevention).

Speed kills. Or, more appropriately, kinetic energy kills. Both the mass and the circulation speed of a travelling vehicle set its intrinsic kinetic energy, which has the property of transforming itself into other manifestations of energy, and that is the source of the mechanical forces that will decelerate and deform the vehicle when a road impact takes place, translating those efforts to the human beings inside or outside the vehicle. Furthermore, as it can be observed in the daily tragedy of traffic crashes, these road impact-related mechanical forces provoke accelerations and direct impacts that when applied upon body tissues have proven to be frequently beyond human tolerances. So, the faster a vehicle travels, the higher the kinetic energy, the higher the mechanical forces that will be exerted upon human bodies, and the higher the potential damage to either motorists or nonmotorists. Similarly, the heavier a vehicle travels, the higher the potential damage to either motorists or nonmotorists. Yet, speed and mass are not the only factors that have a major influence in the outcome of a road crash.

The factors that determine whether a human being survives undamaged, is sentenced to a permanent physical impairment, or fatally dies can be summarized as follows:

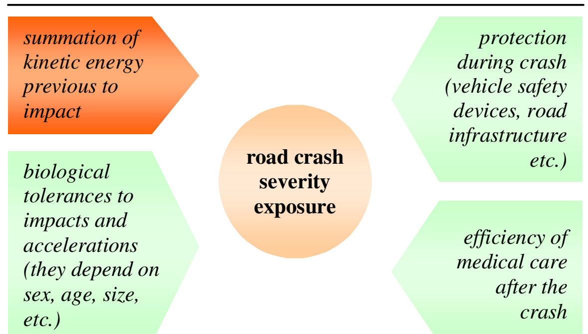


Figure 1. Factors that influence in the severity of a road crash.

A review of the above mentioned factors shows that although all of them affect the severity of the result of a traffic impact, each of them does so in a different way. While biological tolerance, available protection (including both the safety devices present in the vehicle and the road infrastructure), and available medical care can be considered a default in a certain circulation condition, speed is a factor that introduces an uncertainty. In other words, it can be said that a driver travelling on his car on a road has an intrinsic tolerance to injury defined by:

- an inherent biological tolerance to accelerations and direct impacts that will be, for example, lower for an elder male than for a young female (1).
- the protection provided by his vehicle, which will be more efficient if it has received a better rating in test programs such as the New Car Assessment Program (NCAP) (2).
- the protection provided by both the road infrastructure and an emergency environment that will assist him in case of a road crash, a kind of assistance which will be more efficient if he is in a high-income country than in a low-income one (3).

Therefore, the "injury tolerance" for the named driver can be predicted from the mentioned circumstances. Yet, what cannot be predicted are nor the measure of the deceleration he will be exposed to, nor the amount and force of the direct impacts, since all of these depend tightly on the summation of kinetic energy previous to the impact –thus, on the circulation speed–:

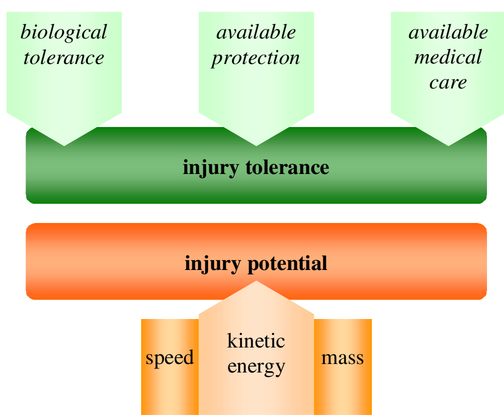


Figure 2. Factors that influence the tolerance to injury and the potential damage in a traffic impact.

As it can be seen, both the mass and the speed of a vehicle should be highly taken into consideration by the driver, since with every kilogram in plus and with every kilometer per hour in plus he is stepping into a higher level of "injury potential" that can be inflicted either to himself or to his fellow human beings. Furthermore, as it is known, speed has greater influence than mass in the value of the kinetic energy of an object, because while mass has a directly proportional influence on this physical dimension, speed has a directly quadratic influence:

$$E_k = \frac{1}{2} m.v^2$$

(E_k = kinetic energy; m = mass; v = speed)

A simple numerical comparison between two vehicles can show how kinetic energy –and "injury potential"– are affected by an increment in mass or in speed. On the one hand, a 1:3 difference in masses corresponds to a 1:3 difference in kinetic energy. In the case of a small car weighting 1.000 kg that circulates at 40 km/h, its kinetic energy is determined at 61,7 kjoule, whereas a SUV weighting 3.000 kg and travelling also at 40 km/h has a three-time higher kinetic energy (185,2 kjoule). On the other hand, a similar small car circulating at 120 km/h has a nine-time higher kinetic energy (555,6 joule) than the one travelling at 40 km/h. A graphical representation of these examples can be found in the following figures:

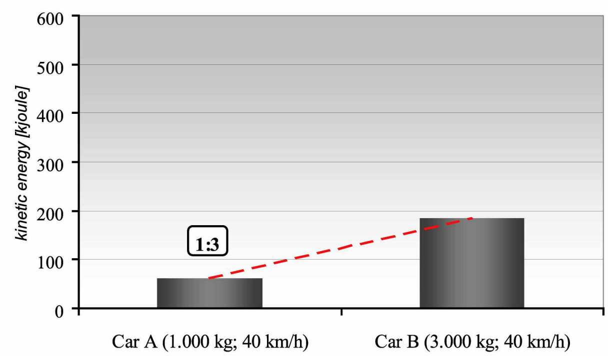


Figure 3. Influence of mass both in kinetic energy and in "injury potential".

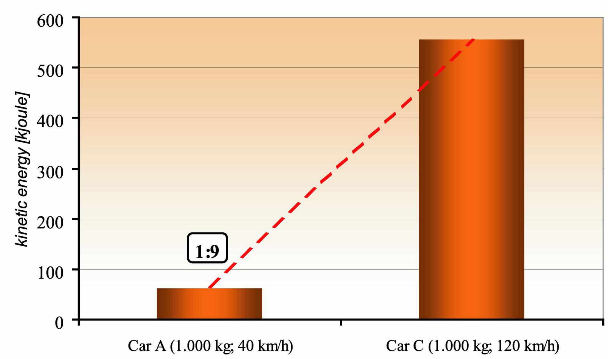


Figure 4. Influence of speed both in kinetic energy and in "injury potential".

So, if it is assumed that for any given situation there is a predictable "injury tolerance", the traffic system must ensure that this named tolerance is enough to compensate any possible "injury potential". It can be argued that the fastest and simplest way of accomplishing this involves adjusting the circulation speeds to safe levels. Furthermore, some experts within the scientific community argue the values of safe circulation speeds:

Table 1.
Recommended travel speed according to the type of infrastructure and traffic, considering current traffic conditions.

type of infrastructure and traffic	recommended travel speed [km/h]
locations with possible conflicts between pedestrians and cars	30
intersections with possible side impacts between cars	50
roads with possible frontal impacts between cars	70
roads with no possibility of a side impact or frontal impact (only impact with the infrastructure)	100

Source: reference 4

However, for many drivers the mentioned speeds may appear absurdly low, specially when most of the vehicles that they are driving are capable of travelling faster than 200 km/h without affecting seriously their handling capabilities or their comfort, and when speeding provides them with both highly intense sensations and considerable benefits. In addition there is a further consideration that may have quite significant influence in the driver's decision to travel fast: road crashes are not as frequent as it is thought. In fact, the United States, which can be taken as a good reference for what happens in high-income countries, bears a rate of crashes per traveled kilometers (including fatal, injury, or property only damage ones) that can be estimated at around one crash every 700.000 vehicle traveled kilometers (5). For an average annual traveled distance of nearly 20.000 kilometers, a typical driver in the United States sustains a road crash, on average, roughly once every 35 years – that is to say, approximately once in his entire driving cycle–. Moreover, in that crash he has a mere 0,06% of chances of receiving fatal injuries (5).

Hence, an average driver that is circulating on a single-lane two-ways road could think: "Why should I keep my circulation speed below 70 km/h if my car can circulate at more than 200 km/h, if it is unlikely that I would get involved in a road crash, and if I can get both pleasure and other advantages while circulating faster?". The answer is simple. Firstly, he should respect the so-called "absurdly low travel speeds" because road crashes are not a frequent event on a single basis, but the overall traveled distances are of such a gigantic proportion that drop by drop they fill an ocean of daily tragedy. As a matter of fact:

– road crashes are the origin of huge economic losses, estimated at 1% of the GNP of low-income countries and 2% for high-income ones, costing to the world about 1,5% of its global GNP (3).
– over a million people lose their lives and dozens of millions sustain some kind of physical impairment as a result of traffic impacts (3).
– the social consequences of such a phenomenon of wide proportions are virtually incalculable affecting mainly the youths who are the most exposed –damaging deeply their family group–; affecting in a terrible way the children and young people that lose their parents; and affecting the society as a whole, which must carry out the resettling of the victims, adapting the general infrastructure (namely buildings, homes, etc.) to the necessities of the dozens of million people that every year must bear some permanent physical impairment.

Secondly, he should respect the so-called "absurdly low travel speeds", because the most serious and fatal injuries happen in crashes at high speeds. Moreover, it can be argued that those named "high speeds" start at a relatively slow 60/70 km/h threshold, at least under the current road conditions, and given the protection capabilities of modern vehicles.

EXAMPLE BOX 1
Estimated average travel speed in fatal crashes in the United States

An analysis using the data available at Fatality Analysis Report Systems (FARS) allows to estimate the average travelling speed of fatal crashes for the years 1994-2002 in the United States. As it can be seen in the following figure, most fatal crashes involve speeds that stretch out between 60 km/h and 120 km/h with a larger concentration in the range 70-90 km/h. The latter represents values within legal circulation limits, and is above the maximum speed at which crashworthiness of automobiles is evaluated in impact test programs.

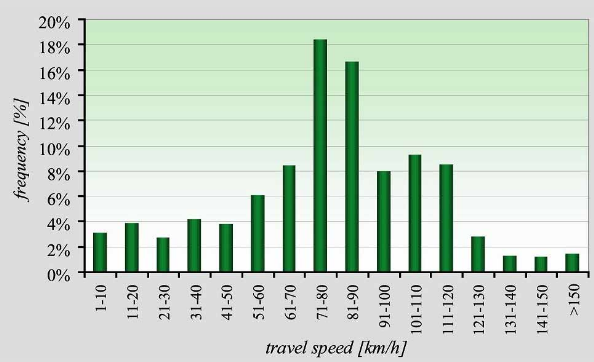


Figure 5. Frequency of registered fatal crashes according to their travel speed in the United States for the years 1994-2002.
Source: reference 6

Finally, he should respect the so-called “absurdly low travel speeds” because the catastrophe of traffic crashes is not going to become less serious in the short-term unless drastic measures are taken. Under current conditions, chances are that by the year 2020 traffic crashes will become the third cause of death in the world (7).

To conclude, this paper does not propose a milestone technological innovation nor it states that the actions taken so far in the field of speed management have been incorrectly directed. Instead, it provides an additional general review to the aspects of severity decrease through speed reduction, and the ways of doing this by available technology, with the intention to encourage everyone who is or will be dedicating great amounts of efforts to diminish the burden of traffic crashes –and who believes that the best way to do so is by a general and synergistic approach– indicating the huge benefits of setting within a reasonable period of time the circulation speeds at values where the human body is capable of undergoing a road crash without serious or fatal injuries.

ROAD TRAFFIC CRASH AND ROAD TRAFFIC FATALITY TRENDS

“Human life and health are paramount. According to Vision Zero, life and health should not be allowed in the long run to be traded off against the benefits of the road transport system, such as mobility. Mobility and accessibility are therefore functions of the inherent safety of the system, not vice versa as it is generally today”. (Sweden’s “Vision Zero”, looking for no fatalities or serious injuries in road traffic).

Surprising as it may be, in the beginning the introduction of the first automobiles had a positive effect in the descent of the mortal victims caused by the means of transportation. This was so because the first vehicles, although rudimentary, could be controlled in a better way than the dozens of thousands of horses used previously in every city. As automobiles developed more weight, power and speed, and the quantity of vehicles increased in a geometric way, traffic crashes began to provoke the first devastating effects, generating among the population greater awareness of the problems caused by such crashes.

Greater awareness resulted in better and safer roads, in better and safer cars, in wiser and more prudent drivers. The factors that lead to a traffic crash were identified, and crash rates began to diminish. Nowadays, in most high-income countries, the rates of crashes per traveled kilometer are far below than that of few decades ago. A huge amount of effort was made in order to manage the factors that lead to a traffic crash, which can be outlined in the following figure:

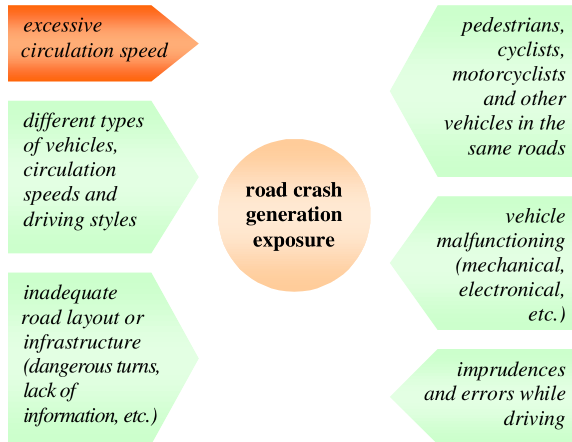


Figure 6. Factors that influence in the generation of a road crash.

Nevertheless, there is a demonstrated close relationship between economic growth and motorization rate, and between economic welfare and traveled distances. The higher the level of economic development and welfare, the greater the amount of motor vehicles, and the larger the quantity of kilometers traveled by each individual (8).

EXAMPLE BOX 2
Increment on the traveled kilometers in the United States

The following figures are taken form the annual report on Traffic Safety Facts by the NHTSA, and show that the United States faces a multiplying phenomenon: every year there are more inhabitants, every year there are more vehicles per inhabitant, and every year the vehicles travel more kilometers. In the 27 years analyzed, the population incremented a mere 34%, while the number of traveled kilometers was over twice-folded as seen hereby:

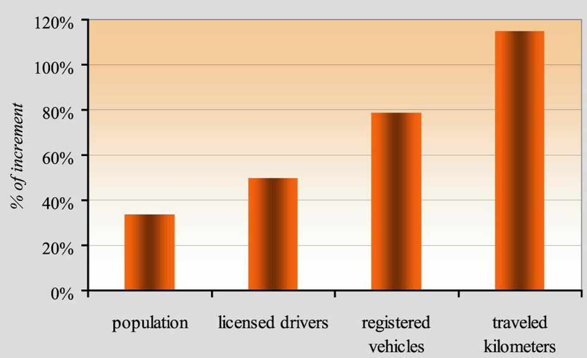


Figure 7. Increment in population, number of licensed drivers, number of registered vehicles and traveled kilometers in the United States between 1975 and 2002.

Source: reference 5

Hence, the key question to answer is: is the crash rate diminishing in such a way to compensate the increment in traveled kilometers, thus generating a lower total quantity of traffic injuries? Though this paper does not answer the question thoroughly, it can be mentioned that the 2004 WHO report on road traffic injury prevention states that a reduction in the total number of traffic fatalities may be expected in high-income countries (taken as a group) for the period 1990-2020 (3). Yet, this may not be the case of all of them.

EXAMPLE BOX 3
Traffic fatality trends in the United States

The 2002 Traffic Safety Facts of the NHTSA (9) highlights that the fatality rate dropped to reach 0,84 fatalities per 100 million vehicle kilometers of travel (VKT) in 2002. The trend for the last decades can be further analyzed in the following figure:

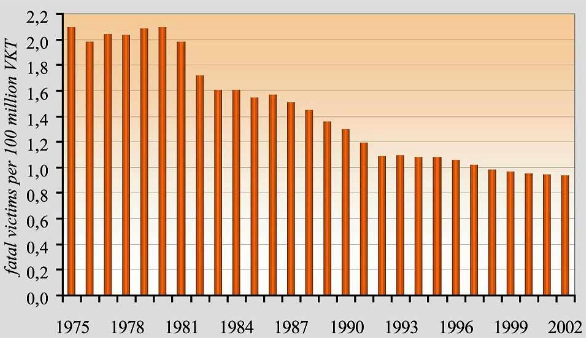


Figure 8. Evolution of the rate of fatal victims per 100 million VKT in the United States for the years 1975-2002.

Source: reference 5

Nevertheless, in the same period the distances traveled experienced a constant increment, as shown hereby:

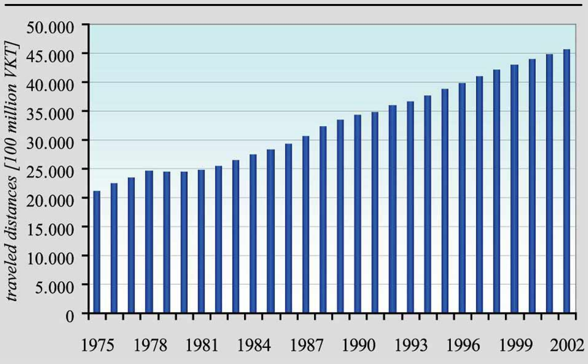


Figure 9. Evolution of the quantity of traveled kilometers in the United States for the years 1975-2002.

Source: reference 5

Therefore, the total number of victims caused by traffic crashes ranged around 40.000. As it can be concluded from the following figure, the situation remained more or less constant for the last decade, with a slight upward tendency:

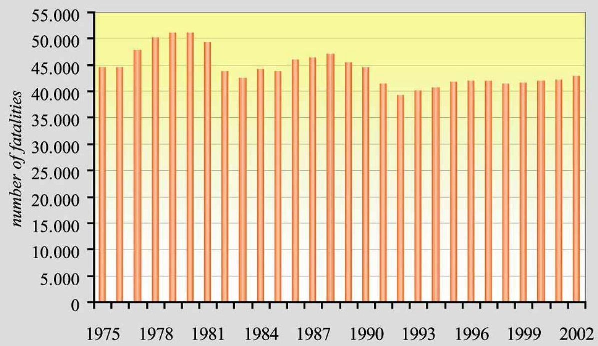


Figure 10. Evolution of total fatalities in road crashes in the United States for the years 1975-2002.

Source: reference 5

On the other hand, what has to be highlighted is that, one way or the other, only 10% of road traffic deaths occur in high-income countries (3). The reduction of road fatalities in these nations is a consequence of decades of harmonized policies and rational traffic management. Almost every index has shown a betterment in the last years, and it can be predicted that in the long-term this will eventually be the case of medium-income and low-income countries, which will benefit from successful measures previously implemented in other countries. But before this happens, things are presumably going to get worse for the vast majority of the world's population.

Firstly, because medium-income and low-income countries do not show at present times diminishing road crash or road fatality rates (3). Secondly, because it can be expected that in the short term a lot of those nations will experience a sharp increment in their currently meagre motorization rate, as they stroll their development path (8); this increment will therefore imply larger quantities of traveled kilometers. Lastly, because most of the measures that must be taken to reduce fatality rates imply medium-term or long-term actions. As far as this last comment is concerned, it can be argued that decades will be spent in the developing world before:

– inadequate road layout or infrastructure are improved.
– structural corruption in the police force and state inefficiency are overcomed so as to ensure successful law enforcement campaigns aiming at limiting speeding, drinking, among other law-breaking habits that compromise road safety.

– new cars attain the highest protection standards available in high-income countries cars.
– older cars are subjected to strict technical inspections and potentially dangerous vehicles are retired from the roads.
– drivers are thoroughly educated both in theoretical and practical expertise so as to drive safely.

To summarize, sustainable economic growth leads to higher levels of motorization, and to steep and fast increments in the quantity of traveled kilometers. But in order to minimize traffic serious or fatal injuries, other aspects of road traffic, related to education, environment and enforcement, have to go along with motorization rate growth. As it can be argued that the mentioned aspects will follow motorization rate growth only in the medium/long-term, an aggravation of the problem is to be expected in the short term. The following figure summarizes this situation:

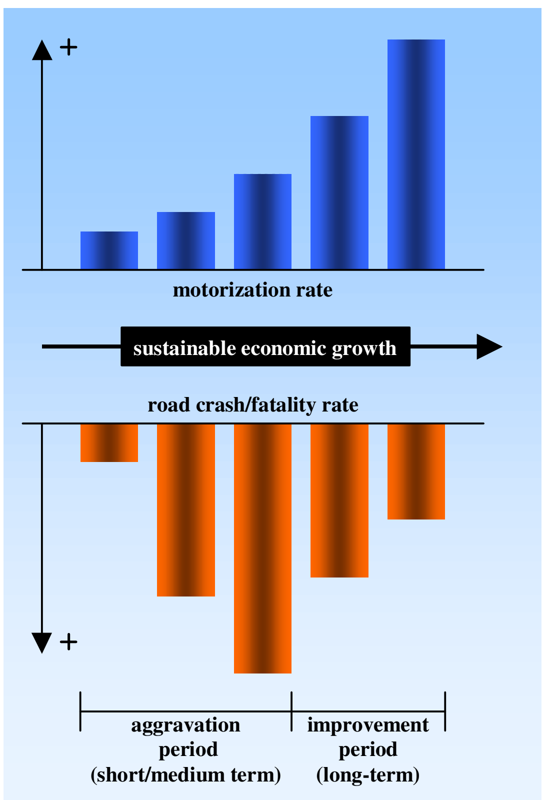


Figure 11. Alleged relationship between long-term sustainable economic growth of a medium-income or low-income country, its motorization rate, and its road crash/fatality rate.

This issue is particularly critical in the countries that are sustaining high levels of economic growth, which leading case is arguably China. Nevertheless, other countries in South Asia (India, for example) will be experiencing abrupt increments in the total quantity of dead and severely injured people as a consequence of road traffic. In fact, the World Bank is estimating that this will be the case of most regions in the world, except (as mentioned) for the high-income countries. The predicted long-term increments in total road fatalities can be observed in the following table:

Table 2.
Predicted increments in total road fatalities in selected regions for the period 1990-2020.

region	change [%]
South Asia	279
East Asia and Pacific	201
Sub-Saharan Africa	144
Middle East and North Africa	129
Latin America and Caribbean	100
East Europe and Central Asia	27

Source: reference 3

To conclude, it can be argued that the world faces a severe problem. It is highly probable that the total number of crashes will rise and only in the long-term (and in the better of cases) it will lower or remain constant. In medium-income or low-income countries, which bear 90% of total road fatalities, the situation is doubtless going to get worse in the short-term, and only in the long-term some progress will be achieved. On the other hand, in high-income countries it is expected a decline in the number of crashes (as most indexes show), though it can be argued that a steep rise in traveled kilometers can compensate the foreseen decrease. Moreover, under current circumstances, if the total amount of crashes does not descend, neither will do the total amount of serious and fatal road injuries. Therefore, it is worth highlighting that the key actions in road safety do not have to aim only at generating fewer crashes but as well –and specially in the short-term– at generating less serious ones.

THE INFLUENCE OF SPEED IN THE SEVERITY OF A ROAD CRASH

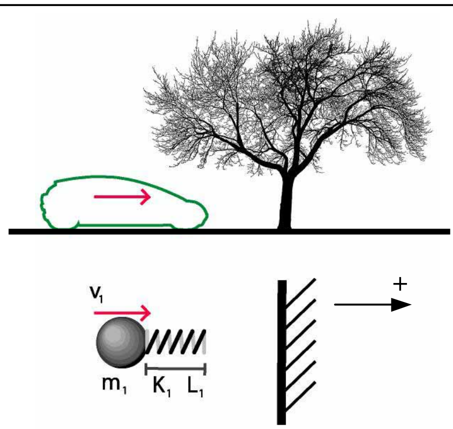
"If a virtually safe system is going to be designed, either the harmful event must be eliminated, or it should not reach the limit of the human tolerance. In the Vision Zero concept, it is assumed that accidents cannot be totally avoided, hence the basis for this concept is built around the human tolerance for mechanical forces". (Sweden's "Vision Zero", looking for no fatalities or serious injuries in road traffic)

Kinetic energy kills a human being in a road crash by means of two different phenomena:

– inflicting direct impacts to the human body as a consequence of occupant compartment deformation or of high-energy direct hits from internal or external objects.
– exposing the occupants to dangerous speed changes that generate harmful "instantaneous" variations of speed (in elastic-type crashes) or harmful accelerations (in plastic-type crashes).

It is clearly understandable that the higher the speed of the impact (that implies higher levels of kinetic energy), the tougher the direct impacts and the higher the aggressiveness of the accelerations the motorists or nonmotorists will sustain. Yet, as mentioned before, the capacity of human beings to turn out to be unharmed in a road crash depends on non-variable aspects such as: an inherent biological tolerance to accelerations and direct impacts; the protection provided by his vehicle; the protection provided by the road infrastructure; and an emergency environment that will assist him in case of a road crash.

For a better understanding of the aspects of crash severity that involve speed, an example of an automobile crashing against a fixed object will be analyzed. The conditions that are going to be modeled are that of a small car weighing 1.000 kg that sustains a full-lap frontal impact against a tree on the side of the road. As many experts agree, an appropriate model for the description of the behavior of an automobile in a crash is the one that proposes a system formed by a single mass and an inelastic spring (10). The general model can be described as follows:



(m_1 = mass; K_1 = stiffness coefficient; L_1 = length of spring; v_1 = speed)

Figure 12. Model for an automobile collision against a fixed object.

To complete the model, the values for the length of the spring and the stiffness coefficient should be set. It is the intention of this paper to use approximate values, since there is a great difference between the various makes and models. Therefore, the numbers that are going to be used, and that have been taken from the consulted bibliography (1, 11), are the following:

$$L_1 = 0{,}65 \text{ m}$$

$$K_1 = 820.000 \text{ N/m}$$

With all the values set, and the assumption that speed remains the only variable of the system, some conclusions will be obtained from a series of evaluations. Before going on, it must be stated that for a given initial kinetic energy, the automobile is able to protect the occupants by means of:

– an external structure that is capable of absorbing a circumscribed amount of kinetic energy.
– a compartment that suffers a determined amount of deformation, if the external structure fails to absorb the whole of the original kinetic energy, and that must avoid the intrusion of external objects which may directly hit the occupants.
– a combination of restrain devices that refrain the occupants from moving forward at the same time that the compartment stops, that should both decelerate them in a safe manner and prevent any dangerous movement in any direction that may lead to a direct impact against the interior of the vehicle.

The first aspect to analyze is how speed affects the ability of the vehicle to absorb the initial kinetic energy, using the modeled type of external structure. Since the vehicle behaves as a mass-spring system, the maximum kinetic energy that can be absorbed is going to be equal to the maximum potential energy that the spring can store:

$$E_p = \frac{1}{2} K.L^2$$

(E_p = potential energy; K = stiffness coefficient; L = length of spring)

For the example analyzed, the numerical value is:

$$E_p = \frac{1}{2}.820.000 \text{ N/m}.(0{,}65 \text{ m})^2 \Rightarrow$$
$$\Rightarrow E_p = 173.225 \text{ joule}$$

When the original kinetic energy (that depends on the impact speed) is higher that the maximum potential energy that the external structure of the vehicle is capable of absorbing, two phenomena can occur:

– if the compartment is rigid enough to sustain the impact without deformation, an elastic-type crash will take place, forcing the cockpit to undergo an "instantaneous" change of speed (and the subsequent extremely high acceleration), which will be transmitted to the occupants since restrain systems are attached to the compartment.

- if the compartment cannot sustain the impact without deformation, a certain degree of intrusion will take place, possibly inflicting direct impacts to the occupants, and limiting the efficiency of restraint system, as the distances between motorists and the interior surfaces become shorter.

It is worth mentioning that in the example analyzed, the speed limit at which the initial kinetic energy exceeds the one that can be absorbed is:

$$E_k \geq 173.225 \text{ joule} \Rightarrow \frac{1}{2} m.v^2 \geq 173.225 \text{ joule} \Rightarrow$$

$$\Rightarrow v \geq \sqrt{\frac{346.450 \text{ joule}}{1.000 \text{ kg}}} \Rightarrow v \geq 18{,}6 \text{ m/s} \Rightarrow$$

$$\Rightarrow v \geq 67 \text{ km/h}$$

Thus, every km/h in plus from 67 km/h will imply a higher level of kinetic energy that will not be able to be absorbed by the external structure, and an increase in the danger of the eventual instantaneous changes of speed or compartment intrusions. The consequences of a variable initial kinetic energy interacting with a fixed capacity of absorption can be analyzed in the following figure, which describes the percentage of the original energy that will not be absorbed by the external structure, for a range of speeds up to 200 km/h (a speed that most modern automobiles can gain):

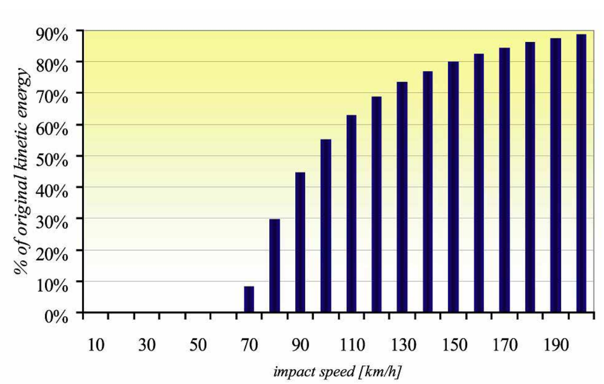
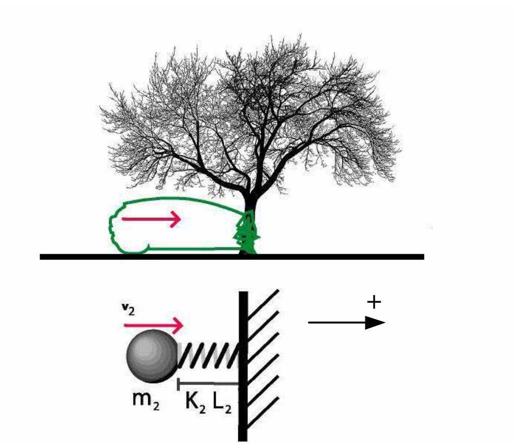


Figure 13. Percentage of original kinetic energy that can not be absorbed by the frontal structure of the automobile of the analyzed example for a wide range of impact speeds.

Therefore, a crash at 70 km/h will imply, for the example that is being analyzed, an initial kinetic energy of approximately 189.000 joule, and of those, approximately 16.000 joule will not be absorbed and will have the capacity to provoke either an instantaneous change of speed or some degree of deformation in the compartment. Whereas, at 130 km/h (a speed within legal limits in most countries), the remaining energy after the crash will be as high as approximately 479.000 joule, which as a matter of fact is nearly three-times higher than the energy that deformed completely the frontal sector of the automobile. Moreover, in the recently named example, the car hits the tree at 130 km/h and, after the frontal structure accomplished its absorbing function, the compartment is still moving at 111 km/h.

A further analysis can be made in order to estimate the second aspect which is the amount of compartment intrusion that will be sustained for every impact speed. In order to do this the previous model will be modified as follows:



(m_2 = reduced mass; K_2 = compartment stiffness coefficient; L_2 = length of compartment intrusion; v_2 = remnant speed)

Figure 14. Model for determining compartment intrusion for an automobile in a high-speed collision against a fixed object.

It is assumed that the compartment behaves in a similar way to the one of the frontal structure, with a reduced mass (since the engine and the front of the car are not influencing the movement) and with a different stiffness coefficient (since as a general rule compartments of automobiles are reinforced to minimize intrusions). Therefore, assuming approximate values, the following parameters are going to be used:

$$m_2 = 700 \text{ kg}$$

$$K_2 = 1.640.000 \text{ N/m}$$

These numbers result from estimating both that 30% of the mass of the vehicle is ahead of the compartment, and that the latter is twice as rigid than the frontal structure. As said before, these may not be the values of an actual vehicle, so the numbers should be considered only rough approximations that are used to simulate in a simplified way the chain of events that take place in a real impact. The third element to estimate is the remnant speed of the compartment after the frontal structure absorbed all of the possible kinetic energy. This can be done by, for instance, isolating the time from the harmonic movement equation, and replacing the expression in the speed equation:

$$\bar{x}(t) = \bar{A}.sin(\omega.t) \Rightarrow t = \frac{1}{\omega}.asin\left(\frac{\bar{x}}{\bar{A}}\right)$$

$$\bar{v}(t) = \bar{v_o}.\cos(\omega.t) \Rightarrow \bar{v}(t) = \bar{v_o}.\cos\left(asin\left(\frac{\bar{x}}{\bar{A}}\right)\right) \Rightarrow$$

$$\Rightarrow \bar{v}(t) = \bar{v_o}.\sqrt{1-\left(\frac{\bar{x}}{\bar{A}}\right)^2}$$

(v_o = speed of impact; x = mass displacement = 0,65 m;
v = mass speed; A = amplitude of movement = $\frac{vo}{\sqrt{\frac{K}{m}}}$)

In this way the set of equations is complete, and the extent of compartment intrusion can be calculated for a given impact speed. The results for the assumed values are summarized in the following figure:

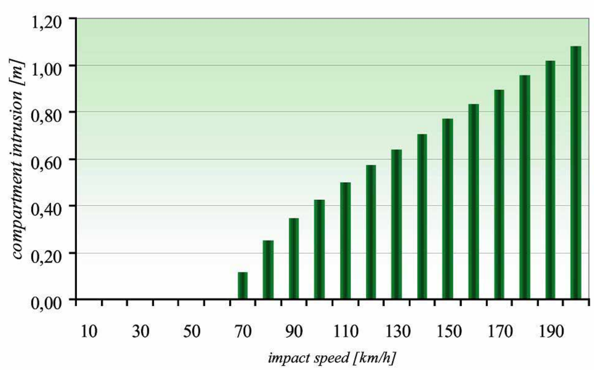


Figure 15. Extent of compartment intrusion in the automobile of the analyzed example for a wide range of impact speeds.

It must be remembered that the figures that are expressed above correspond to a theoretical and simplified model of the extremely complex phenomena that take place in a road crash. Once this is taken into consideration, it can be argued that the initial speed of the impact is determinant as to the extent of compartment intrusion. As it can be observed in the example a road crash against a fixed object at 100 km/h may lead to such a deformation eliminating all of the space between the frontal occupants and the dashboard or the steering wheel.

Therefore, why is it that the stiffness coefficient of frontal structures is not set in order to absorb the whole of the kinetic energy of the impact? The reason for this is that, as mentioned, kinetic energy kills either by inflicting direct impacts or by exposing occupants to dangerous acceleration levels. So, a vital trade off must be reached. If the stiffness coefficient is set so as to absorb all of the kinetic energy of the impact, high levels of acceleration are going to be produced. On the other hand, in order to minimize acceleration-related injuries, the value of the stiffness coefficient must be limited, and therefore some degree of compartment intrusion will take place.

Regarding this, there is a key issue that arises: what should be the design speed for the appropriate stiffness coefficient? Should it be 64 km/h (as in the impact tests that are being carried out and that represent the possible average speed of frontal impacts)? Should it be 130 km/h (as in the case of assuming that an automobile may sustain a road impact at the maximum allowed circulation speed)? Or should it be the top speed of the vehicle (as in the case of assuming that most drivers circulate at speeds that exceed the legal limits, and that even though it is highly unlikely that a great number of road crashes take place at such a speed, it is convenient to establish some degree of safety coefficient)?

It is not the intention of this paper to indicate which would be the appropriate design speed, though the most serious of all three cases is going to be considered. Therefore, the behavior of the example vehicle will be analyzed on the basis of a new stiffness coefficient, set so as to absorb all of the kinetic energy of an impact against a fixed object, up to speeds of 200 km/h. To do so, the following equation will be used:

$$\bar{A} = \frac{\bar{v}_o}{\omega} = \frac{\bar{v}_o}{\sqrt{\frac{K}{m}}} \Rightarrow K = \left(\frac{\bar{v}_o}{\bar{A}}\right)^2.m$$

(A = amplitude of movement; v_o = speed of impact;
ω = angular frequency; K = stiffness coefficient; m = mass)

In order to simplify the analysis, no change in either the length of the amplitude of movement (0,65 m) or in the mass of the vehicle (1.000 kg) will take place. Therefore, the new suitable stiffness coefficient can be calculated as follows:

$$K = \left(\frac{\bar{v}_o}{\bar{A}}\right)^2.m \Rightarrow K = \left(\frac{55{,}5\text{ m/s}}{0{,}65\text{ m}}\right)^2.1.000\text{ kg} \Rightarrow$$

$$\Rightarrow K \cong 7.300.000\text{ N/m}$$

It is worth mentioning that the resulting stiffness coefficient is almost nine-times higher than the originally assumed one. In a practical situation this will mean incrementing the mass of the vehicle (which will result in a different “ideal” stiffness coefficient), redesigning the frontal structure, as well as using appropriate materials. Therefore, a thorough analysis must be done to determine the feasibility of the proposed change. Yet, it must remembered that this paper is only a general study of the subject, as a reference to the phenomena of speed and its relationship to crash severity, so the above values should be considered only as a result of a series of theoretical and simplified assumptions.

Deeming these aspects, the average acceleration that the compartment would sustain can be analyzed, for the considered range of impact speeds. The reason for calculating the average acceleration instead of the peak acceleration is that when studied together with the time of exposure, it may give a more accurate reference to the dangers related to the acceleration process. Regarding this, it is worth highlighting that there is scarce theoretical knowledge about human resistance to acceleration and almost no empirical experience (1) since the last extensive and thorough tests were made just to determine the risks that future NASA astronauts would undergo; on top of that, such tests were made using air-force pilots –that do not represent the average human being– and more than half a century ago. Yet, it is possible to determine that the resistance to acceleration diminishes as the time of exposure to it increases, and that there are senses and directions more favorable than others (1).

Going back to the analysis, the average acceleration can be calculated as:

$$a_{avg} = \frac{\int_{t_o}^{t_f} a\,dt}{\Delta t} = \frac{A\omega.\left(\cos\left(\omega.t_f\right)-1\right)}{t_f}$$

(a_{avg} = average acceleration; a = acceleration; t = time; t_o = initial time; t_f = latest time; A = amplitude of movement; ω = angular frequency)

Considering that:

$$a_{max} = v_o.\sqrt{\frac{K}{m}}\ ;\ \mathrm{t_o} = 0;\ \mathrm{t_f} = \frac{\pi}{2}.\frac{\bar{v}_o}{a_{max}};$$

$$\omega = \frac{a_{max}}{\bar{v}_o}\ ;\ \bar{A} = \frac{\bar{v}_o^{\,2}}{a_{max}}$$

(a_{max} = peak acceleration; K = stiffness coefficient; m = mass; v_o = impact speed)

The first equation can be expressed as:

$$a_{avg} = 2.a_{max}.\frac{\cos\left(\frac{\pi}{2}\right)-1}{\pi} = -\frac{2}{\pi}.a_{max} \Rightarrow$$

$$\Rightarrow \boxed{\left|a_{avg}\right| = \frac{2}{\pi}.v_o.\sqrt{\frac{K}{m}}}$$

On the other hand, the following equation will allow to deduce an important aspect:

$$t = \frac{T}{4} \Rightarrow t = \frac{\pi}{2\omega} \Rightarrow \boxed{t = \frac{\pi}{2}.\sqrt{\frac{m}{K}}}$$

(t = time; T =harmonic movement period; ω = angular frequency; K = stiffness coefficient; m = mass)

Thus, the time at which the acceleration is exerted upon the compartment (and subsequently transmitted to the occupants by means of the restraint devices) does not depend on the impact speed; a conclusion that could have been also drawn from the fact that a single-mass/inelastic spring system is used for modeling the behavior of the crashing vehicle. So, the higher the impact speed, the higher the acceleration of the compartment. And as the time is non variable, it is clearly understandable that higher levels of acceleration exerted on the same period of time represent higher levels of “injury potential”.

For instance, for the example that is being analyzed, at 70 km/h the average acceleration of the compartment can be estimated at 108 g, for a time of 0,0184 seconds. At 200 km/h, the average acceleration can be estimated at 308 g, for the same period of time (the peak acceleration in this last case reaches 484 g). The complete numbers for the considered range of speeds can be hereby seen:

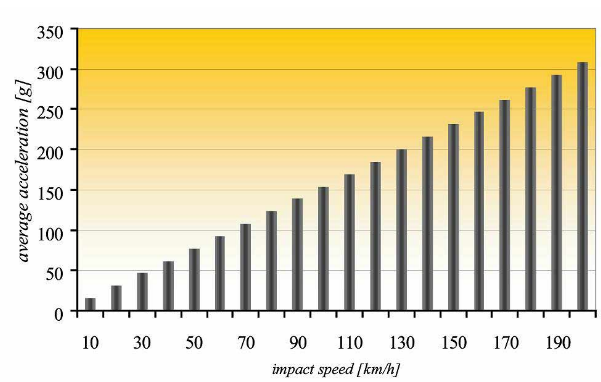


Figure 16. Average acceleration for the compartment of a vehicle designed to absorb completely the kinetic energy of road crashes with an impact speed up to 200 km/h.

As mentioned before, it is difficult to predict the extent of injuries that a human being will sustain under the circumstances described above. Yet, as a general reference, NCAP directives and standards consider that the exposure to peak accelerations below 60 g (for the chest) or 80 g (for the head) for a 3 ms period of time is relatively safe, and values exceeding these are considered dangerous. Unfortunately, a direct comparison can not be done since different periods of time are involved, but it can be argued that an average 108 g exposition for 0,0184 seconds will generate some degree of irreversible damage to a human being (it must be remembered that the acceleration exposure of the compartment is considered similar to the one the occupants will sustain, as they are attached to it by means of the restrain devices). Moreover, the mentioned values correspond to an arguably low 70 km/h impact speed.

Therefore, in the case of an automobile that crashes against a fixed object, speed affects crash severity as follows:

- if the initial kinetic energy exceeds the one that can be absorbed by the frontal sector of the car, a dangerous phenomenon of compartment intrusion may take place at speeds as low as 70 km/h leading to direct impacts to the occupants.
- if the frontal sector of the car is designed so as to absorb all of the kinetic energy of high-speed impacts, acceleration inflicted upon occupants may seriously injure them.

These circumstances have been numerically exemplified in figures 12 through 16, and can be summarized as follows:

Table 3.
Estimated compartment intrusion for selected speeds for the first analyzed example (unmodified frontal sector stiffness coefficient).

impact speed [km/h]	compartment intrusion [m]
70	0,12
130	0,64
200	1,08

Table 4.
Estimated average and peak acceleration for selected speeds for the second analyzed example (modified frontal stiffness coefficient) in a 0,0184 seconds period.

impact speed [km/h]	acceleration [g]	
	average	peak
70	108	169
130	200	315
200	308	484

Nevertheless, every aspect that has been analyzed so far corresponds to a single vehicle crashing into a fixed object (which by the way is not the most common of traffic impacts). It can be argued that speed has an overwhelming influence in many other extremely relevant road crash settings, namely:

- pedestrians have a 90% chance of surviving a car impact at 30 km/h, while at 60 km/h the chance is merely 10% (3). In low-income and medium-income countries, which bear 90% of all road traffic fatalities, most of the fatal crashes involve pedestrians, cyclists or motorcyclists.
- the vast majority of high-speed impacts in a motorcycle have proven to be fatal, since it can be argued that the motorcyclist lacks the minimum protection that is needed to overcome unharmed any kind of traffic crash. For instance, in the United States, while the rate of killed car passengers per 100 million VKT was 0,8 in 2002, the same rate reached 40,8 (which represents a 51:1 relationship) as regards motorcyclists (5).
- in head-on collisions between two vehicles a lot of compatibility issues arise (that include the differences in masses and the behavior of the frontal structure, which is specially related to the way in which frontal rails interact). Therefore, a relatively safe speed for a crash against a fixed object may not be equally safe for a head-on collision between two vehicles (12), which account for the most common road crash in high-income countries (5).

To conclude, it must be remembered that circulation speed is associated to a defined kinetic energy, which in time is related to a certain “injury potential”. This injury potential is opposed by non variable aspects such as human biological tolerance, available vehicle and environment protection to impacts, and the efficiency of medical assistance. Regarding this last issue it must be stated that:

- firstly, human biological tolerance can not be modified in order to survive serious impacts without any important damage.
- secondly, vehicle and environment protection to impacts can be modified, and there is evidence that progress has been made over the last years (specially in high-income countries), but impacts at certain speeds imply serious technological problems that do not allow to ensure the prevention of all serious or fatal injuries.
- thirdly, the efficiency of medical assistance can be modified, but as in the case of vehicles and road infrastructure, the system is designed to be able to act in the case of “survivable” impacts, mainly at low-speed or medium-speed crashes.
- lastly, it can be argued that the circulating speeds are beyond safe levels, as road fatalities and injuries statistics show.

Therefore, and considering that life and health should be given preference in regards to the benefits of the road transport system, reality shows that the fastest way to drastically reduce the daily tragedy of traffic crashes is to lower the circulation speeds. Because, as theoretical and empirical evidence demonstrate, lower circulation speeds mean lower quantity of serious and fatal road impacts. Lower circulation speeds mean lower quantity of serious and fatal road injuries. Lower circulation speeds mean better life and health.

VOLUNTARY DECREASE OF SPEED CIRCULATION

"Speed, it seems to me, provides the one genuinely modern pleasure" (Aldous Huxley, Wanted. A new pleasure, in Music at night, and other essays, 1931).

Speed kills. Yet it is longed for. Fast cars have always been the object of desire of the average driver in almost every country. Nowadays, most automobiles –even those vehicles that are intended mainly for family use such as station-wagons and SUVs– are equipped with extremely powerful engines that allow them to travel at very high speeds (which are far beyond legal circulation limits). It is true that buying a car with a 250 km/h top speed does not necessarily mean that the driver is going to break the law by circulating at speeds higher than the legal ones, but fast cars represent an almost unbearable temptation, for the simple reason that travelling at high speeds (along with other advantages that will be named later) provides a thrilling experience.

In 1931, "Brave new world" author Aldous Huxley wrote an essay about the necessity of inventing a new pleasure for humanity. One that would abolish our individual solitude during some hours per day, something that would reconcile us with our fellow men in a burning exaltation of affection and that would made life not only worthy of being lived in all its aspects, but also divinely beautiful and transcendent. He figured that this could be achieved by a kind of drug, one of such nature that the following morning we could wake up with a clear head and a harmless organism. And he stated that the most similar thing to this new drug (though vastly far from the ideal) was the drug of speed. In Huxley's opinion, the inebriant speed effects begun at 90 km/h, and at 110 km/h an unprecedented sensation was felt. Unfortunately, nowadays the combination of vibration-less and extremely comfortable automobiles and ample and largely straight roads makes the sensation described by Huxley more than 70 years ago to be felt at much higher speeds (arguably beyond 160 km/h).

These among many other reasons that are not going to be thoroughly analyzed in this paper explain why drivers long for high speeds. And as an answer to the market's demand, these days automobiles are every time faster, heavier, and more powerful, most of them allowing stable driving at speeds that a few decades ago only sports cars permitted. As a result, automobiles are able to develop every time more kinetic energy, thus they bear higher "injury potential".

EXAMPLE BOX 4
Evolution of maximum developable kinetic energy of the Volkswagen Golf

The Volkswagen Golf is one of the best-selling cars in the automobile history. More than 22 million units of this model have been sold over its 30-year life. Since its first appearance in 1974 five series of this highly popular car have been introduced, and with every new development, power has increased, mass has grown, and maximum speed has augmented. To illustrate this point, in 1976 the most powerful vehicle within the model range was the newly born GTI which had the next selected characteristics:

- *maximum power: 110 CV.*
- *mass: 830 kg.*
- *maximum speed: 180 km/h.*

By 2005 the most powerful vehicle within the model range is a more extreme GTI with these selected characteristics:

- *maximum power: 200 CV (+ 82%).*
- *mass: 1.372 kg. (+ 65%).*
- *maximum speed: 235 km/h (+ 31%).*

It can be argued that an adequate way of assessing this increment is the analysis of the maximum developable kinetic energy which gathers in a single expression the increment of both the mass and the speed, and it is also a valid index for the named "injury potential". From the analysis it can be concluded that the most powerful vehicle available in 2005 experienced an almost threefold increase in its maximum developable kinetic energy when compared with the most powerful one in 1976. Furthermore, the less powerful vehicle in 2005 (Golf 1.6 3 door) is capable of developing a maximum kinetic energy way higher than the one the most powerful car was able to develop in 1976. All of this can be observed in detail in the following figure:

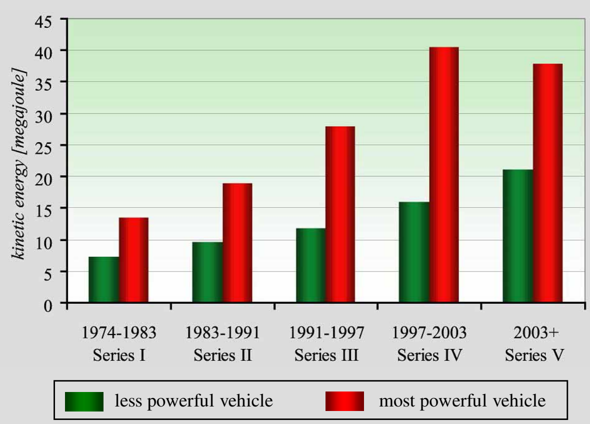


Figure 17. Evolution of maximum developable kinetic energy for each series of the Volkswagen Golf.

Source: references 13, 14

Moreover, in a global context where everyone seems to be constantly hurrying up and time is more precious than gold, high circulation speeds are said to be beneficial to road safety since it is argued that:

- it takes less time to arrive to destination (the risk of suffering a road crash is reduced since the driver is less time exposed to traffic).
- overtaking actions are done faster and therefore in a safer way, reducing the chance of a head-on collision.
- a better concentration level is achieved while circulating at high speeds rather than at low speeds, where fatigue and boredom frequently induce errors.

There is no comprehensive study that supports the above arguments, and even in the case they were true, they all refer to advantages in the field of crash prevention. Yet, the core argument of this paper is that circulation speeds must be lowered not only because it is highly probable that fewer crashes will occur, but –particularly– because under current circumstances low-speed impacts alone provide a considerable chance either to motorists or nonmotorists to survive a road crash without serious or fatal injuries.

Unfortunately, fast driving brings tangible and immediate benefits for the driver that is able to end his trip without sustaining a road crash (which, as mentioned before, is a infrequent event that happens –at least in high-income countries– at an estimated rate of one crash every 700.000 vehicle traveled kilometers). Furthermore, fast driving is socially fostered, since individual success is generally represented by very expensive, very powerful, and very fast automobiles. On the other hand, the benefits of slow driving are far less discernible –specially in the very short term–, as they serve mainly the community as a whole, and they only arise by means of permanent prudent behavior over a long period of time. The conclusion that can be drawn from the aspects analyzed in this section (among others) is that it is unlikely that drivers will reduce willingly their circulation speeds. Furthermore, it is unlikely that they will keep the circulation speeds within legal limits, unless they are emphatically forced to do so.

To conclude, it can be expected that if every factor with an influence in road safety remains at current state:

- cars will continue to provide higher maximum speeds every time.
- circulation speeds will be higher and higher.
- a voluntary decrease of speed can not be expected neither in the short-term nor in the long-term.
- road crashes will happen at higher speeds every time.

EXAMPLE BOX 5
Average travel speed trend for fatal road crashes in the United States

A second analysis using the data available at Fatality Analysis Report Systems (FARS) allows to estimate the trend for average travel speed of fatal crashes for the years 1994-2003 in the United States. Since a seasonal behavior is observed (fatal crashes in winter happen at lower speeds) a 12-month mobile mean was calculated. The results shown as follows reveal a slight –though constant– upward tendency:

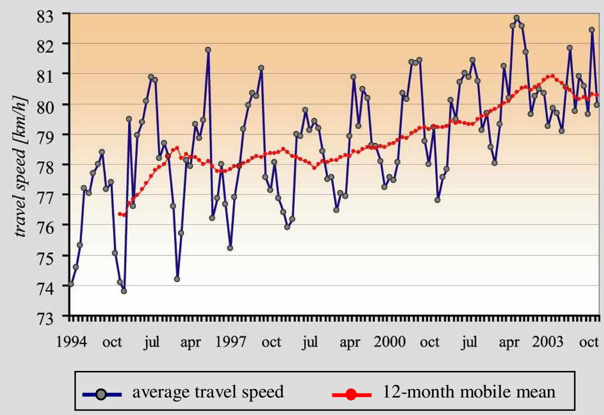


Figure 18. Evolution of the average travel speed of registered fatal crashes in the United States for the years 1994-2003.
Source: reference 6

SPEED LIMITATION THROUGH GPS TECHNOLOGY

"Until recently, responsibility for crashes and injuries was placed principally on the individual road user. The system designers and enforcers –such as those providing the road infrastructure, the car making industry and the police– are responsible for the functioning of the system. At the same time, the road user is responsible for following basic rules, such as obeying speed limits and not driving under the influence of alcohol. If the road users fail to follow such rules, the responsibility falls on the system designers to redesign the system, including rules and regulations." (Sweden's "Vision Zero", looking for no fatalities or serious injuries in road traffic).

Electronically-controlled devices are widely used in modern motor vehicles. They skillfully manage fuel injection, stability control, emergency braking, and (in certain circumstances) circulation speeds. Regarding the latter, the following devices can be named:

- standard cruise control (the desired circulation speed is set by the driver, and the system sends a signal to the engine or braking system either to accelerate or decelerate the vehicle, maintaining the desired speed even when conditions change –e.g.: road passing over a hill–).

– adaptive cruise control (this system automatically adjusts speed in order to maintain a proper distance between vehicles in the same lane).
– speed limiter (car makes such as Mercedes-Benz, BMW, Volkswagen or Volvo set a maximum speed of 250 km/h for all of their automobiles by acting in the fuel injection system).

Therefore, it can be argued that from the technological point of view, it is possible to set the maximum circulation speed in order to remain below the legal limit. But before that happens, some system-related and vehicle-related conditions must be assured, namely:

– a digital database of every road, whether urban rural o motorway, should be available, complemented by a speed limit database.
– every vehicle should be able to store that information and update it periodically, as well as be able to set its current position (through GPS technology and an on-board computer).
– speed limiter and cruise control should closely interact with the determined position of the vehicle and the corresponding speed limit, therefore managing the maximum circulation speed.

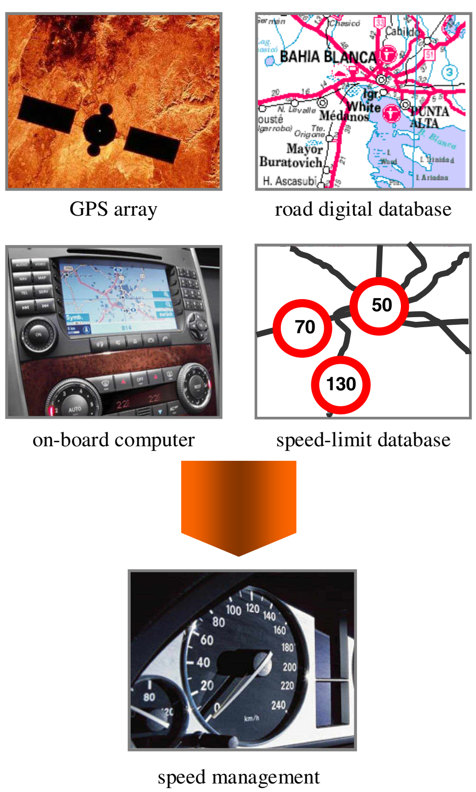


Figure 19. Speed management through GPS technology.

On this regards, it is worth mentioning that at present times there are a number of programs that deal with this aspect of circulation speed management, such as the ISA program.

EXAMPLE BOX 6
ISA (Intelligent Speed Adaptation) Program

In a three-year period, an ISA program test was conducted in Sweden. Some ten thousand voluntary drivers tested an array of technical systems, involving "warning", "informative" and "supportive" ISA devices. If the driver drove too fast, light and sound signals were activated in the warning or informative systems. In the supportive system the acceleration pedal offered resistance, which could be overcome by following a kick-down action. Regarding this, the following test results can be highlighted (15):

– *a clear decrease in speed violations at all speed limits took place.*
– *lower average circulation speeds of vehicles provided with ISA provoked a decrease in average and maximum circulation speeds of vehicles not provided with ISA.*
– *drivers using ISA kept better headway and showed more consideration.*
– *there was no change in travel times, despite lower circulation speed (fewer stops and braking situations).*
– *both fuel consumption and emissions decreased.*

Yet, when considering a short-term global implementation of systems that are similar to the ISA program many issues arise, namely:

– although many current motor vehicles are provided with on-board computers and a GPS navigation system, the majority of motor vehicles lack these vital components. If only vehicles provided with on-board computers were to be compelled to set their circulation speeds to legal limits the great differences in circulation speed would probably worsen the situation. Thus, every motor vehicle should be provided with a speed management system before implementing such programs, which can only be achieved in the medium-term or in the long-term, unless some kind of fostering policy by the governments took place. The situation is particularly sensitive in low-income and medium-income countries, where GPS technology is mostly unavailable and governments lack practical means to implement such systems.
– it can be argued that mandatory systems will provide better results as regards speed decrease, yet informative and supportive phases will probably have more adhesion in the first steps of the implementation, thus reducing at first the efficiency of the system.

On the other hand, the advantages of such systems are overwhelming, among which:

- circulation speed can be efficiently controlled, so as to be largely kept below legal limits.
- circulation speed limits can be set according to the road characteristics (urban, motorway, etc.)
- circulation speed limits can be adjusted in real-time to fit variable conditions, such as bad weather, snow, fog or any other unusual event.
- circulation speed limits can also be set according to the motor vehicle characteristics and maintenance condition, as well as to the driver conduct, expertise and experience (with the aid of a digital identification device, or similar).

To conclude, since speed management is such a sensitive matter to road safety, and both the drivers and the system have proven to be unable to maintain the circulation speeds below legal limits, it is highly necessary to modify some aspects of the road system so as to ensure the circulation at safe speeds; and when pros and cons are weighed, it is probable that the mentioned speed management through GPS technology will bring largely more benefits than inconveniences.

CONCLUSIONS

"Any effective response to the global challenge of reducing traffic casualties will necessarily require a large mobilization of effort by all those concerned at the international, national, and local levels" (World Health Organization – World report on road traffic injury prevention).

Speed kills. And it is going to continue doing so unless huge efforts are made in order to set within a reasonable period of time, circulation speeds at values where the human body is capable of undergoing a road crash without serious or fatal injuries. Over the last years many successful traffic safety measures gave place to a decrease in injury and fatality rates; although this only happened in high-income countries which bear 10% of total world fatalities. On the other hand, it is expected that the quantity of traveled kilometers will suffer a worldwide increase in the next years. Therefore, if the current conditions remain unchanged, road crashes will become one of the main causes of death within a short period of time. Moreover, it can be argued that the fastest and most efficient way to minimize the daily tragedy of road crashes is through the reduction of circulation speeds to comply with the legal limits, or even better, to remain within safe limits.

This paper concludes that a feasible way to achieve the necessary circulation speed management is through a mandatory intelligent speed adaptation system, which integrates GPS arrays, road and speed limits digital databases, and in-vehicle currently available hardware and software (namely on-board computer, speed limiter, and cruise control). However, it is probable that this will be possible in the medium-term or long-term, so this paper also proposes to enhance the efforts directed towards speed management, doing so in a general and synergistic approach, involving government, industry, and university, as well as public and private safety-related organizations.

To conclude, it must be remembered that more than a million people are killed annually (and that dozens of million bear some kind of permanent physical impairment) due to road crashes that happen at speeds that exceed human and system tolerances. Therefore, the sooner a safe speed management is achieved, the sooner speed will stop killing.

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